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A signal correlator and data logging system

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Summary

Equipment has been built for converting two slowly varying signals to digital form and computing the coefficient of correlation between them at preset intervals. The results of the calculations together with some of the parameters used may be punched on paper tape.

Issued under the authority of

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Research Department, Engineering Division,
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A SIGNAL CORRELATOR AND DATA LOGGING SYSTEM

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A SIGNAL CORRELATOR AND DATA LOGGING SYSTEM

G.H. Millard, B.Sc., M.Inst.P., M.E. Bailey, B.A. and H.M. Price, B.Sc.

1. Introduction

Studies of the propagation of ultra-high frequency (u.h.f.) television signals across the English Channel have required a knowledge of the degree of correlation between signals in two particular instances. First, when a wanted signal is subject to fading, the depth of the fades may be reduced by switching between two signals which have traversed different paths or have different frequencies or polarisations (diversity reception). The benefit to be gained depends on the lack of correlation between the signals. Second, the subjective effect of co-channel interference depends on the degree of correlation between wanted and unwanted signals when both are time dependent.

In the projected application, the signals to be examined for correlation would normally be the voltages proportional to signal strength obtained from recording receivers tuned to the television sound carrier. Such receivers commonly have a logarithmic law. The maximum rate of variation of the signals from natural propagation effects was expected to be about 1 Hz but reflections from aircraft were expected to increase this to 10 Hz or more.

At the sampling rate required to register the fastest variations, and with the equipment left unattended for several weeks, the total amount of raw data is enormous. The device was therefore conceived as a data reduction system. This is achieved by fast on-line processing which produces and stores cumulants. At the end of a preset period, the cumulants may be directly output onto punched paper tape or subjected to further programmable processing before being output. Fig. 1 shows the arrangement of the complete data-logging system. A photograph of the signal correlator and timing unit is shown in Fig. 2.

The concept and definition of correlation coefficient does not of itself make any assumptions about the statistical law of fading. But any deduction made with it almost certainly will. In some instances a log-normal distribution (i.e. a normal distribution when the levels are expressed in decibels) may be appropriate, in others a Rayleigh distribution may be more suitable. It should be borne in mind that the signal correlator is not designed to determine the validity of a particular distribution although the log-normal distribution is tacitly assumed for some of the subsidiary parameters.

2. Theory

The statistics of experimental results are deduced in depth in various standard text books[1,2,3] and only a summary is given here.

Given n experimental values of each variate, $(x_i,y_i)_{i=0}^{n-1}$ the expectation values for the means are

$$\bar{x} = \Sigma x_i/n \qquad \text{all sums assumed from 0 to n−1}$$
$$\bar{y} = \Sigma y_i/n$$

The expectation of the product is equal to the product of the expectations provided that the variables are independent (which is not generally the case). Thus, for x, y

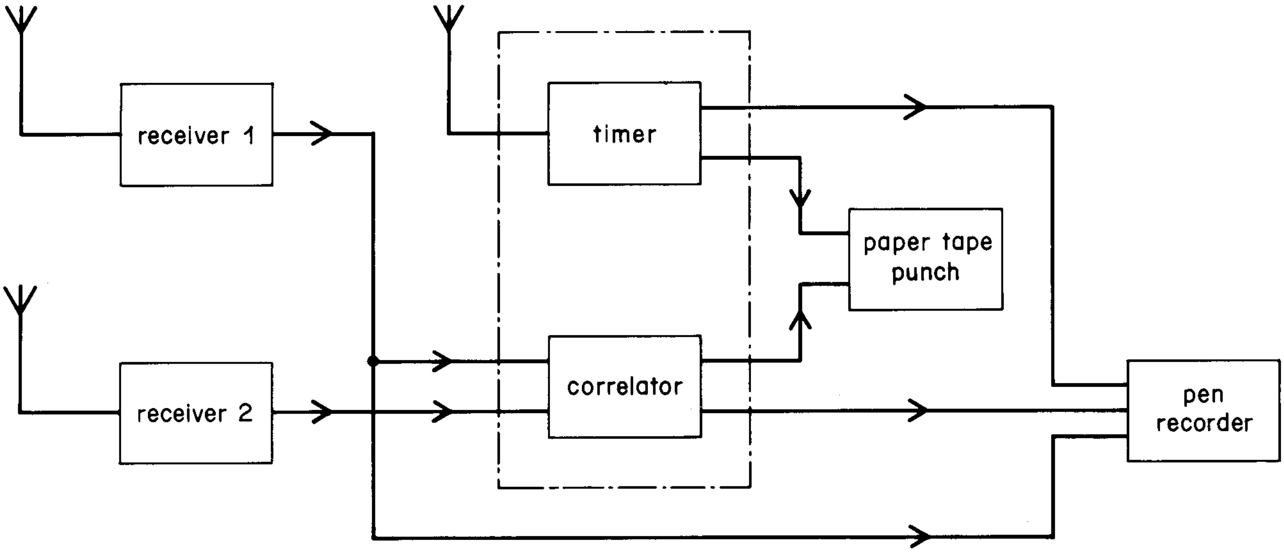

Fig. 1 - Schematic diagram of the data logging system

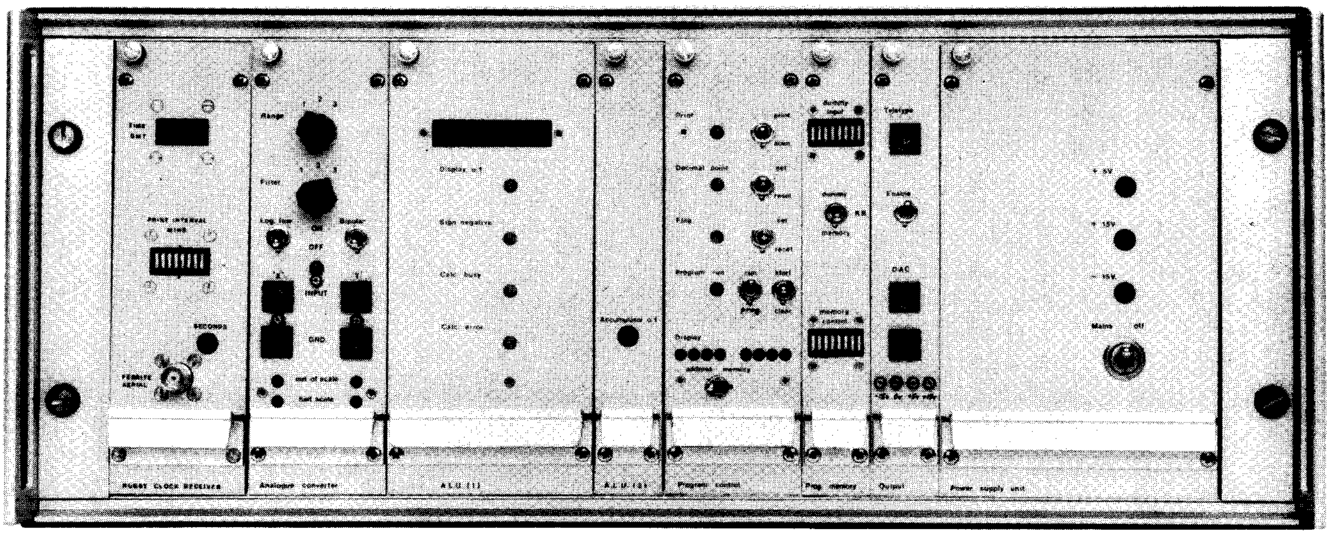

Fig. 2 - The signal correlator

independent

$$\bar{x}\,.\,\bar{y} = \overline{x.y} = \Sigma x_i y_i/n \qquad \ldots\ldots\ (1)$$

The standard deviations are the spread in the distributions (if normal) about the true mean. The squares of these, or variances, may be best estimated by:

$$Sx^2 = \Sigma(x_i - \bar{x})^2/(n-1)$$

$$Sy^2 = \Sigma(y_i - \bar{y})^2/(n-1)$$

These expressions may be written in the case for $n \gg 1$ as

$$Sx^2 = \overline{x^2} - \bar{x}^2 \qquad \text{where } \overline{x^2} = \Sigma x_i^2/n$$

$$Sy^2 = \overline{y^2} - \bar{y}^2 \qquad \text{where } \overline{y^2} = \Sigma y_i^2/n$$

Similarly the covariance of x and y, which is a generalisation of the variance, may be estimated by:

$$S_{xy}^2 = \overline{xy} - \bar{x}\,.\,\bar{y}$$

Now for independence, by equation (1),

$$(S_{xy}^2) \text{ independence} = 0$$

Whilst if $x \equiv y$ it is clear that

$$(S_{xy}^2) \text{ equality} = S_x^2 = S_y^2$$

The estimator for the correlation coefficient ρ is found to be

$$\rho = \frac{S_{xy}^2}{S_x\,.\,S_y}$$

which is zero for independence and unity for equality, i.e. $+1 \geqslant \rho \geqslant -1$. Moreover, ρ does not change if x and y are multiplied by a constant factor, or if a constant is added.

It should be noted that the correlation coefficient may be computed from sums of up to the second order:

$$n, \quad \Sigma x, \quad \Sigma x^2, \quad \Sigma y, \quad \Sigma y^2, \quad \Sigma xy \qquad \ldots\ldots (2)$$

where n is the number of samples. The same sums may be used to calculate means and standard deviation and to carry out linear regression analysis.

3. Philosophy of signal correlator

The arithmetic required is conveniently divided into two parts. The first part must be performed at the sampling rate and involves the production of the cumulants given in (2). These are continually updated using relatively simple and fast digital arithmetic, taking care that there is adequate storage space for the large numbers so generated.

The second part involves the further processing of the cumulants and this can be performed slowly without detriment, since it is required only infrequently. A programmable desk calculator chip is used for this part of the operation. This has the advantages both of economy and versatility; any other parameter involving the same cumulants may be obtained by merely changing the program.

It is probable that applications will arise that could not be foreseen when the unit was designed. Provision has been made therefore for a variety of peripheral devices on both input and output.

4. Data input

It was stated earlier that the inputs of the correlator will usually be obtained from recording receivers, making use of the voltage provided for driving a pen recorder. This slowly-varying voltage is fed into a buffer amplifier and a low-pass filter before quantisation by an 8-bit analogue-to-digital convertor (a.d.c.). It is, of course, important to ensure that the input voltage lies within the range of the a.d.c. In order to assist the initial setting, a front panel light indicates readings greater than half scale (levels 128—255); a multi-meter may also be used. A further light operates if the signals exceed the a.d.c. range and an indication is given on the output data, since the calculation of correlation coefficient would then be invalid.

The field-strength recording receivers referred to above are rather old, valved equipments, likely to be phased out within the next few years. A replacement receiver, now under development, will have a digital output in b.c.d. form. Provision is made, therefore, for input data in this form.

One of the applications planned for the correlator is the investigation of correlation between a fading wanted signal and sources of co-channel interference (c.c.i.). A design of c.c.i. measuring receiver exists which has a digital output in binary form.[4] The correlator has been designed to take data directly in this form also.

Provision is made also for manual entry of data in order to check the operation of the correlator and to facilitate programming. This is achieved by replacing the analogue convertor with a small keyboard.

5. Arithmetic logic units

8-bit input quantisation was chosen as adequate for signal strength representation. Input quantising accuracy determines the accuracy of the parameters in the output. The cumulants are valid to five decimal figures, due to this effect, after 45 minutes of sampling at 25 Hz.

The equipment can process data at up to about 500 co-ordinate pairs per second. For following signal strengths, a range of 6 to 25 pairs per second is normal. The choice will be the fastest rate which does not lead to accumulator overflow in the required processing period.

Each cumulant is stored as a 32-bit binary number allowing approximately 45 minutes processing at 25 Hz before overflow at f.s.d. inputs, and about 3 hours at half f.s.d. inputs. This processing is carried out in a 32-bit accumulator, the heart of the apparatus. The cumulant storage is organised as a "stack", so that the input processing is a cyclic routine. Fig. 3 shows a block diagram of the arrangement.

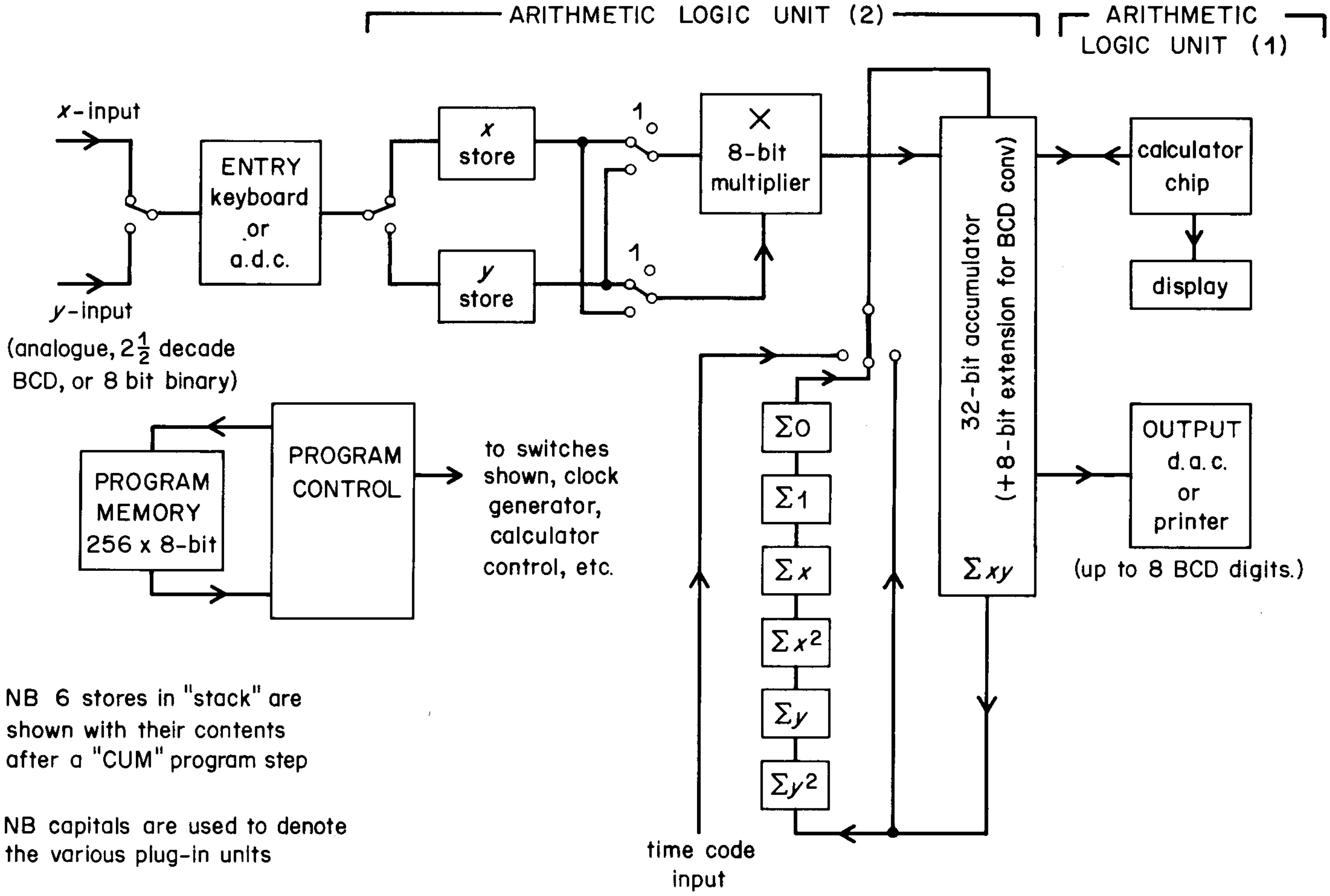
ARITHMETIC LOGIC UNIT (2)
ARITHMETIC LOGIC UNIT (1)
x-input
y-input
(analogue, 2½ decade BCD, or 8 bit binary)
ENTRY keyboard or a.d.c.
x store
y store
1
1
× 8-bit multiplier
32-bit accumulator (+8-bit extension for BCD conv)
Σxy
calculator chip
display
OUTPUT d.a.c. or printer
(up to 8 BCD digits.)
Σ0
Σ1
Σx
Σx²
Σy
Σy²
time code input
PROGRAM MEMORY 256 x 8-bit
PROGRAM CONTROL
to switches shown, clock generator, calculator control, etc.
NB 6 stores in "stack" are shown with their contents after a "CUM" program step
NB capitals are used to denote the various plug-in units

Fig. 3 - Schematic diagram of signal correlator

Final processing of the cumulants is carried out in binary-coded decimal (b.c.d.) numbers by a desk calculator chip. Conversion of the 32-bit binary cumulants to 10 digit b.c.d. numbers is a routine carried out by the accumulator. The calculator chip takes converted numbers from the accumulator, but the reverse procedure is also possible, thus allowing the stack to serve the dual purpose of cumulant and temporary calculation storage. The calculator chip used is the Texas Instrument TMS 0117NC 10 digit decimal arithmetic processor, which is one of the TMS 0100 family of MOS/LSI calculator chips, specially hard-programmed for use as a building block in larger systems.

For permanent records, the accumulator output is converted to ASCII coded characters and printed out on punched paper tape or teletype.

6. Programming the signal correlator

Although the equipment is dedicated to the input routine of producing the cumulants, the order and complexity of the overall procedure which utilises these is completely pre-programmable. The program control can address a memory of up to 512 words of 8 bits. Alternatively, the 8 bit program codes may be entered manually to effect a program.

The set of program steps available are listed in the Appendix, together with their 8 bit code and mnemonic. Note that branch instructions are included. The calculator chip is not capable of computing the square root. Consideration has therefore been made in the design of program steps to allow the creation of a cyclic routine for the square root, which is required for the correlation coefficient, standard deviations etc.

The memory consists of up to 18 SN74188A programmable read-only memories (PROMs), each holding a block of 4 lines, each of 8 words. For each of the 8 possible block positions of 32 directly addressable lines, there is a choice of one of two PROMs selected by a front-panel switch. Since PROM storage is permanent, this allows some flexibility in program without the need of re-plugging units. The two remaining PROM locations are not directly addressable.

The program in use currently, named "CORR", produces and outputs the following:

the time	t (including status information, in the event of a malfunction)
number of samples	$n = \Sigma 1$
average value of x	$\bar{x} = \Sigma x / n$
standard deviation in x	$Sx = \sqrt{\overline{x^2} - \bar{x}^2}$
average value of y	$\bar{y} = \Sigma y / n$
standard deviation in y	$Sy = \sqrt{\overline{y^2} - \bar{y}^2}$
correlation coefficient	$= \dfrac{Sxy^2}{Sx . Sy}$

The form of this output is given in detail in Section 8, below.

7. The timing unit

The operations of the system which need timing information are

(i) signal sampling rate
(ii) the initiating of the calculation of the correlation coefficient
(iii) the identification of the output data.

Since the unit is to operate without attention, it is desirable that the clock used for identifying the output information should reset automatically after any interruption to the mains power supply. This is achieved by using a receiver to read the time radiated from Rugby on 60 kHz. All other timing information is derived from the mains supply.

The 60 kHz receiver is a tuned radio frequency receiver operated with an external ferrite rod aerial. The transmitted carrier is interrupted once per second for 100 mS. At the end of each minute a time code is transmitted which gives the time in GMT. Fig. 4 shows the form of the time code. The time in hours and minutes is displayed on the front panel. These figures may be read into the accumulator at any time on demand. The unit is also provided with a light display of the pulses at each second, this being of assistance in positioning the aerial. The aerial coils are provided with a screen to minimise static pick-up. Nevertheless, the level of static interference is likely to determine the range at which the receiver may be used. Occasional misreading of the time code can be tolerated since this will usually be apparent from the output record.

The mains timer performs two functions. Firstly, it provides a clock stream which controls the data sampling rate. Secondly, it tells the signal correlator when to finish accumulating data and calculate the correlation coefficient. Both these quantities may be varied. The sampling rate is presetable between 5·9 Hz and 25 Hz by internal wiring change. The print interval may be chosen in one minute steps between 1 minute and 165 minutes by means of a front panel switch.

Some consideration has been given to the provision of a day counter. This could have some benefit in identifying the time of the output data. It might also be used to clear the calculator once per day to guard against any error from persisting for a long period. The day counter would have to be triggered by the Rugby clock but should not be dependent on a single reading. The logic required is involved and provision has been deferred until

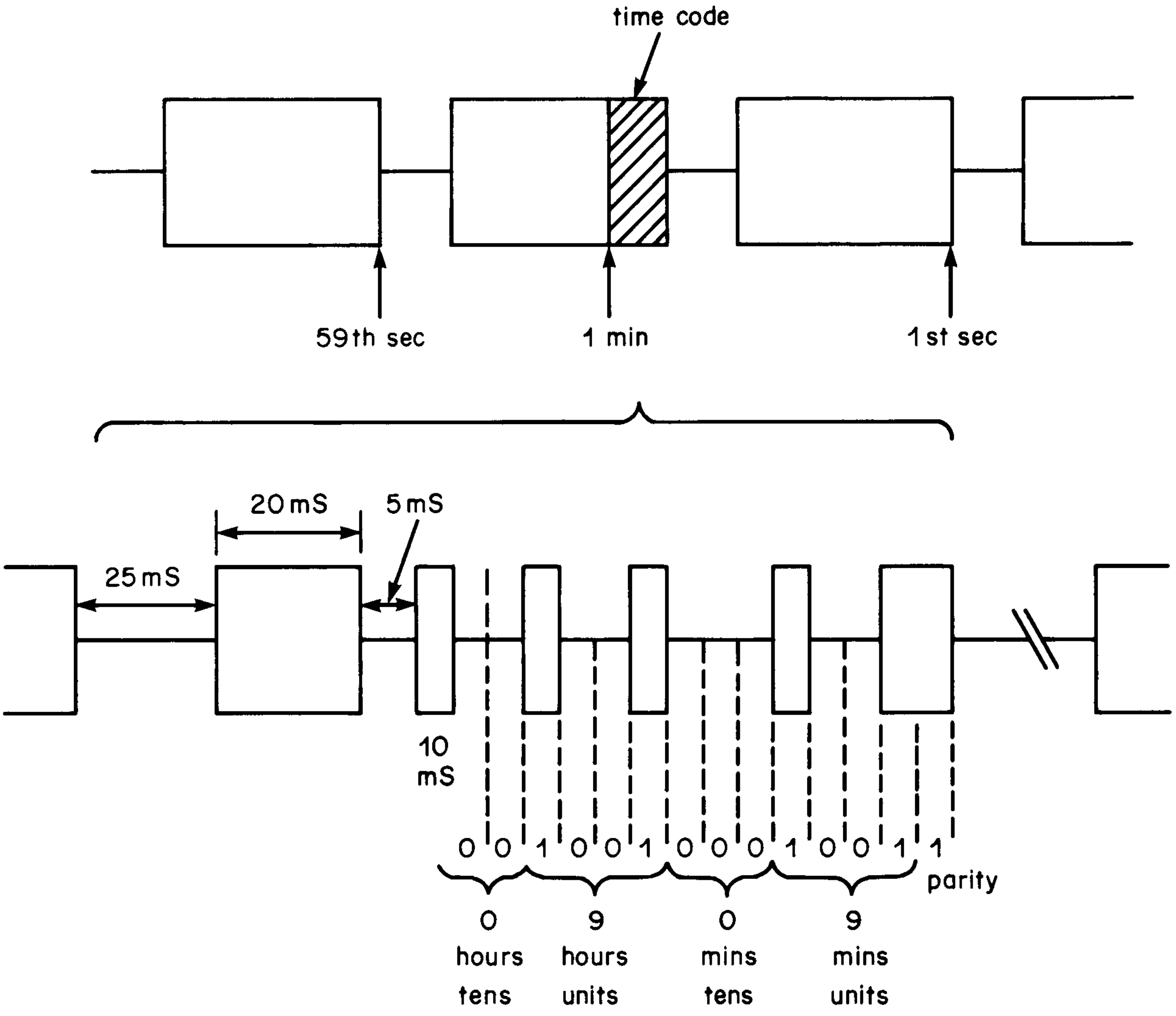

Fig. 4 - Rugby 60 kHz transmission: time code

a need is established.

8. Data output

Output will normally be in digital form on punched paper tape using a Data Dynamics Type 1133 punch. This will allow further processing of the data at base as well as the editing out of periods when the transmitter was inoperative.

Initiation of the output routine results in the generation of a record of ASCII characters beginning with 'line feed' (LF) and ending with "carriage return" (CR).

```
   TIME        N       XBAR        SX        YBAR        SY     CORR COEFF

   13.05     2479.    127.549    65.101    127.017    66.161    0.94168
   13.07     2483.    127.546    63.440    127.019    65.384    0.87549
10013.09     2488.    128.707    63.997    128.165    65.921    0.87840
   13.11     2487.    127.540    63.437    127.008    65.397    0.87571
   13.13     2488.    127.503    58.378    126.997    55.242    0.53204
   13.15     2496.    127.561    55.637    126.977    48.961    0.26085
   13.17     2496.    127.608    55.644    127.057    48.977    0.26140
```

Fig. 5 - Teletype output

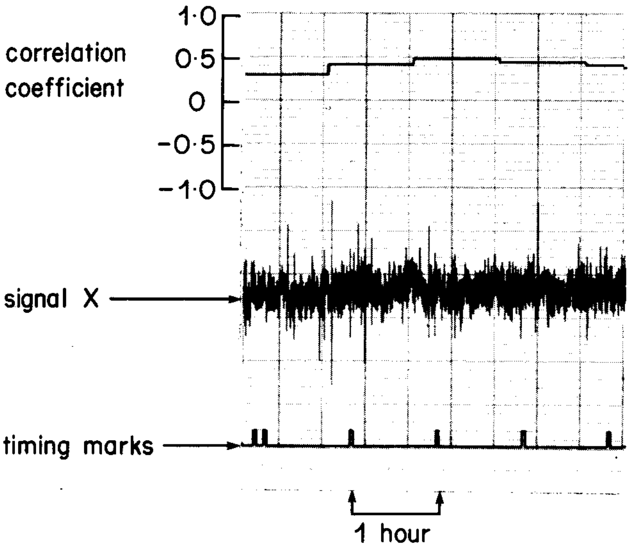

Fig. 6 - Example of chart recording

As arranged for program "CORR" the record is of 72 characters composed of seven 10-character words containing the numerical outputs listed in Section 6. The first word is complex. It starts with a character which indicates the occurrence of input overflow, accumulator overflow or calculator error. This is followed by two zeroes in the locations reserved for a day counter. The remainder of the word is occupied by the time. If all is well no error character or zeroes will appear. Fig. 5 shows a sample output printed on a standard teletype machine, the column headings being added manually. Note the indication of input overflow at time 13.09.

The record for one output comprises 72 characters including control characters. In addition there are a few nulls in order to space the records. This requires about 2 seconds to punch. The length of paper tape for one output is 208 mm so that a 300 mm reel will last for 30 days when the output occurs every 30 minutes.

In addition to the parallel output for paper tape punch, a serial output is provided for direct use with a teletype machine. An external power supply is then required.

During the initial use of the equipment it is planned to operate a pen recorder as well, since this may help with the editing of the numerical record. It is intended to record one or both of the signal inputs and the times at which print-out is initiated. A digital-to-analogue convertor has also been provided so that one channel may be used to record the correlation coefficient. Fig. 6 shows the form of this recording.

9. Testing the system

The provision of the facility of manual data entry gives ample means of checking that the intended calculations are being carried out correctly. A more comprehensive check of the whole system is, however, desirable. In order to achieve this, the output of an oscillator at 6 Hz was divided into two components, the relative phase of which could

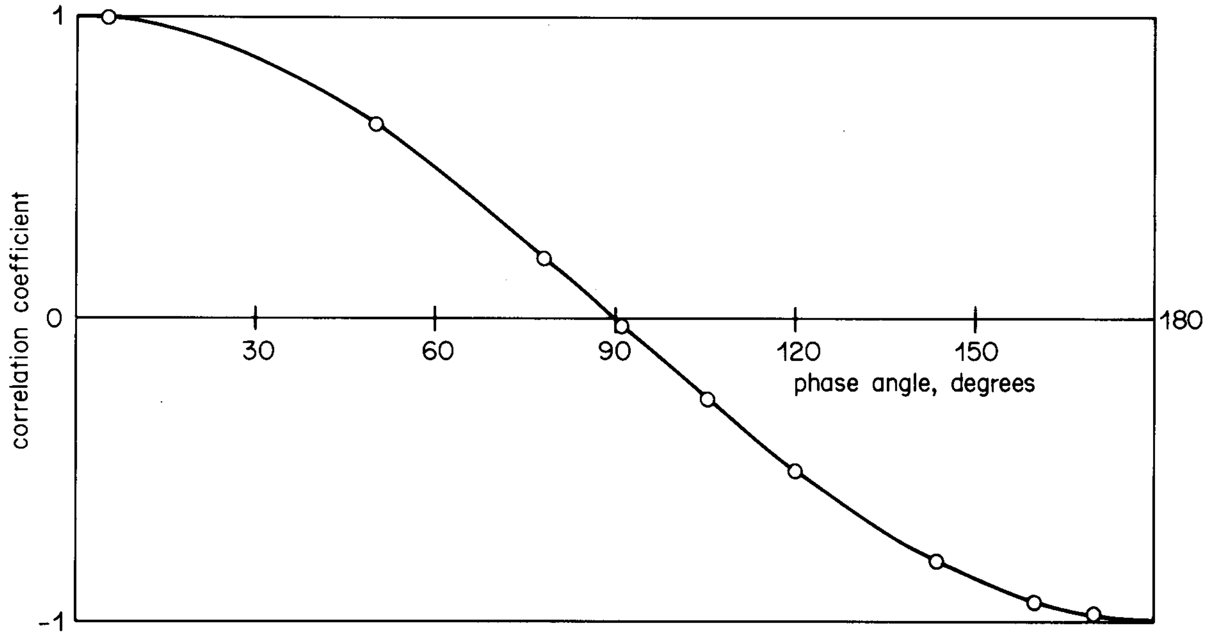

Fig. 7 - Correlation of sine waves

be varied. The indicated correlation coefficient is plotted in Fig. 7 against the phase difference as measured on an oscilloscope. It may be seen that the theoretical curve is followed within the accuracy of measurement. The output shown in Fig. 5 was obtained during this test.

Further testing will be needed under more practical conditions and the availability of a pen record should be of help here. Initial setting of input levels will need to be done with care, making allowance for possible signal peaks, in order to avoid too frequent input overflow. Careful editing will be necessary to exclude invalid results, obtained for example when the wanted transmitter is not radiating.

10. Applications to other problems

The signal correlator was designed for a specific type of problem. The design incorporates a degree of flexibility so that questions of use beyond the original scope will inevitably be raised. Basically, the equipment may be used to investigate any phenomenon which is a simple function of the cumulants given in (2). For example, an earlier investigation was concerned with the ratio of two signals. This is equivalent to the difference between the outputs of logarithmic receivers and could have been processed by the signal correlator to give mean values, standard deviations, etc.

The unit is not suitable for any process involving the sorting of data. Thus it cannot determine median values or fractional parts of an arbitrary signal distribution.

11. Conclusions

Prototype equipment has been constructed to determine the coefficient of correlation between two r.f. signals. Mean values and standard deviations may also be determined. The results may be accumulated over a period of up to about one hour before being punched on paper tape or recorded in analogue form. The equipment has undergone laboratory trials and field trials are now being planned.

The equipment is a considerable advance on previously-available techniques and should permit valuable studies of propagation phenomena.

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APPENDIX

Program set for signal correlator

Program Control Instructions	**Mnemonic**	**Meaning**
0 0 0 0 0 0 0 0	CNT	Continue
″ 0 1 1 0	RTN	Return
″ 0 1 1 1	PNT	Print
″ 1 0 0 0	D5	Set decimal point to 5
″ 1 0 0 1	D3	Set decimal point to 3
″ 1 0 1 0	END	End
″ 1 0 1 1	IN1	Increment counter 1
″ 1 1 0 0	SFG	Set flag
″ 1 1 0 1	CRF	Clear flag and counters
″ 1 1 1 0	STP	Stop
″ 1 1 1 1	DZR	Enter decimal zeroes
Accumulator µ-Programs:		
0 0 0 1 1 0 0 0	↓T	Roll time
″ 1 0 1 0	↓C	Roll clear
″ 1 0 1 1	↓R	Roll down
″ 1 1 0 0	←O	Overlay
″ 1 1 0 1	→E	Enter
″ 1 1 1 0	BCD	Convert to BCD
″ 1 1 1 1	CUM	Cumulate data
Calculator µ-Programs:		
0 0 1 0 0 0 0 0	0	Enter 0
″ 0 0 0 1	1	Enter 1
″ 0 0 1 0	2	Enter 2
″ 0 0 1 1	3	Enter 3
″ 0 1 0 0	4	Enter 4
″ 0 1 0 1	5	Enter 5
″ 0 1 1 0	6	Enter 6
″ 0 1 1 1	7	Enter 7
″ 1 0 0 0	8	Enter 8
″ 1 0 0 1	9	Enter 9
0 0 1 1 0 0 0 0	CRC	Clear calculator
″ 0 0 0 1	=	
″ 0 0 1 0	x	
″ 0 0 1 1	÷	
″ 0 1 0 0	+	
″ 0 1 0 1	INC	Increment calculator
″ 0 1 1 0	–	
″ 0 1 1 1	DCC	Decrement calculator
″ 1 0 0 0	INO	Increment to O/F
″ 1 0 0 1	DCU	Decrement to U/F
″ 1 0 1 0	SHR	Shift right
″ 1 0 1 1	SHL	Shift left
″ 1 1 0 0	EXC	Exchange operands
0 0 1 1 1 1 1 1	RST	Reset calculator, acc. O/F and Input O/F
Program Branch Instructions:		
0 1 0 X X X X X	GSB	Gosubroutine XXXXX000
0 1 1 X X X X X	IFNEG	if –ve go to XXXXX000
1 0 0 X X X X X	IFFG	if flag go to XXXXX000
1 0 1 X X X X X	IFNFG	if no flag go to XXXXX000
1 1 0 X X X X X	IN2UN	Increment counter 2, unless carry go to XXXXX000
1 1 1 X X X X X	DC1UN	Decrement counter 1, unless zero go to XXXXX000
1 1 1 1 1 1 1 1	DLT	Delete code (no operation)

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